

Qualitative validation of CAD-based simulations of NBI-induced prompt fast-ion losses against IRTV measurements in KSTAR

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1. Background & motivation: why validate CAD-based prompt-loss predictions?
2. NuBDeC: CAD-to-simulation framework for fast-ion wall loads
3. Experimental strategy: dedicated KSTAR L-mode discharges + IRTV
4. Results: parameter scan (I_p , B_T , beam source) vs. simulation
5. Conclusions & outlook: toward a surrogate model and digital twin

Background & Motivation

Engineering detail governs fast-ion heat loads

Modern devices are geometrically “crowded”

- Heating ports, cooling channels, diagnostics $\Rightarrow$ real, **non-axisymmetric** engineering geometry
- NBI power deposition and PFC heat loads cannot be captured by idealized, toroidally symmetric models
- Localized peaks arise at **leading edges and limiters**

CAD-to-simulation tools exist ...

- Field-line / orbit tracing through 3D CAD: SMARDDA, HEAT; 3D orbit following: ASCOT
- Being assembled into AI-augmented digital twins (DIII-D, MAST-U in NVIDIA Omniverse)

... but validation is limited

Experimental confirmation that CAD-based predictions reproduce the measured **3D global heat-load footprints** — including localized leading-edge peaks — remains scarce, yet it is a **prerequisite** for trusting these tools in design and between-shot operation.

Precedent: W7-X fast-ion IR validation (Wolf et al., Phys. Plasmas 2019) — not prompt-loss only.

Goal

Qualitative experimental validation of NBI-induced **prompt fast-ion loss** (bad-orbit loss) heat-flux predictions by the CAD-based orbit-following code **NuBDeC**, against **IRTV** measurements on KSTAR lower PFCs.

- Dedicated KSTAR session (Nov. 19, 2025, 4 hours, 23 discharges)
- Scan of $I_p = 400 / 500 / 600$ kA, $B_T = 1.7 / 1.8$ T, beam sources NB1C, NB2A/B/C
- Beam-on/off IRTV ΔT maps (4–7 s window) vs. NuBDeC prompt-loss heat-flux maps rendered at the fitted IRTV camera view
- First benchmark that **isolates NBI prompt loss** from thermal-ion and ELM-driven signals

A step toward quantitative predictive modeling for future devices (ITER, CPD, DEMO) that accounts for engineering details.

NuBDeC: CAD-based prompt-loss simulation

Monte Carlo orbit-following code (Rhee et al., Phys. Plasmas 2019)

- Modular, unified **CAD-to-simulation** pipeline
- High-performance fast-ion-wall **collision detection** on CAD-derived unstructured meshes
- Per-face heat flux from NBI-induced prompt losses mapped onto the **3D PFC surface**
- CAD categorization links every mesh face to its engineering component (divertor, poloidal limiter, passive stabilizer)

Prediction

Because the pipeline operates on as-installed 3D geometry, it predicts **non-axisymmetric, locally peaked** loss footprints at leading edges and limiters.

Inputs per shot

- Magnetic equilibrium (EFIT g -file)
- Fitted n_e , T_e profiles from Thomson scattering
- Beam source geometry, energy, power

Physics knob: toroidal drift controls prompt loss

Prompt loss (also called **bad-orbit loss**): first-orbit loss of beam ions born on loss orbits, deposited on PFCs within one poloidal transit. Larger **toroidal (curvature/ ∇B) drift** $\Rightarrow$ wider loss orbits $\Rightarrow$ more prompt loss.

Drift in circular geometry (Rhee et al., Phys. Plasmas 2019, App. B; Miyamoto 2016):

$$V_D \simeq \frac{m}{eB_0 R_0} \left(v_{\parallel}^2 + \frac{v_{\perp}^2}{2} \right), \quad T = \frac{2\pi q R}{v_{\parallel}}$$

$$D = \frac{V_D T}{2\pi} \simeq \frac{m q R}{e B_0 R_0} \frac{v_{\parallel}^2 + v_{\perp}^2/2}{v_{\parallel}} \xrightarrow{v_{\perp} \ll v_{\parallel}} q \rho_{\parallel} = \frac{r}{R} \frac{m v_{\parallel}}{e B_p}$$

- $I_p \downarrow \Rightarrow B_p \downarrow$, $q \uparrow \Rightarrow D \uparrow$ ($D \propto 1/I_p$)
- Smaller $v_{\parallel}$ at fixed E_b (smaller $v_{\parallel}/v$, e.g. smaller tangency radius) $\Rightarrow D \uparrow$ through $v_{\perp}^2/2v_{\parallel}$
- B_T : $q \propto B_T$ and $\rho_{\parallel} \propto 1/B_T$ cancel $\Rightarrow$ weak effect

Testable predictions

- $I_p \downarrow$ (600 $\rightarrow$ 400 kA): loss $\uparrow$
- B_T (1.8 $\rightarrow$ 1.7 T): weak change
- NB1C ($R_{\text{tan}} = 1.245$ m) vs. NB2A (1.56 m): smaller $v_{\parallel}/v$ at birth $\Rightarrow$ NB1C loses more

Heat-flux peaks expected at **leading edges** on the passive-stabilizer shield / divertor and at the **poloidal limiter**.

Experimental setup

Discharge scenario designed to isolate prompt loss

Diverted L-mode, lower single null (LSN)

- Held **below the L–H transition** $\Rightarrow$ no H-mode / ELM-driven core-ion loss
- RF heating only at startup; effects excluded within the 4–7 s observation window
- LSN steers lost ions into the **IRTV-monitored region**, away from the thermal-ion footprint on the divertor
- NB power as high as achievable without L–H transition (1.25–1.5 MW total) to maximize the fast-ion population

Beam timing (per shot)

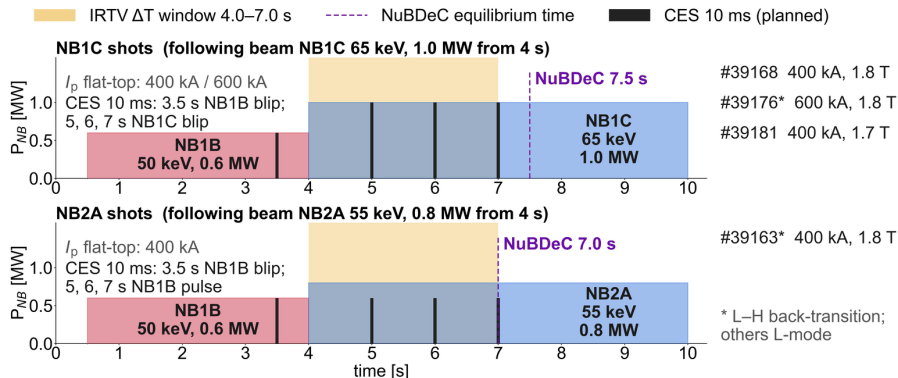
- Baseline: NB1B @ 50 keV, 0.6 MW (0.5–4 s, sustains plasma; no ion loss)
- Following beam under test: 4–10 s (NB1C @ 65 keV or NB2A/B/C @ 55 keV)
- Beam blips/pulses (10 ms) for CES

Diagnostics

- Tangential IRTV (100 Hz), PFC thermocouples
- Thomson (n_e , T_e), ECE, TCI, CES (T_i)
- Neutron detectors

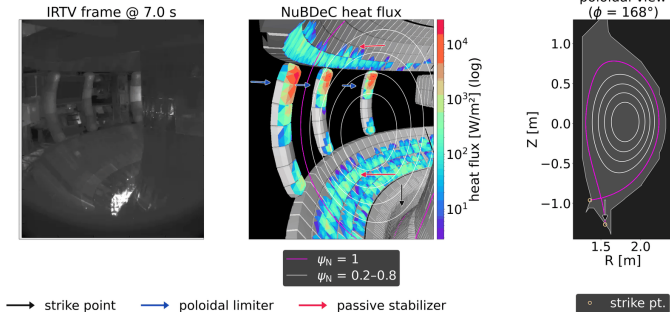
NBI setting and the IRTV ΔT window

I_p and B_T scans with NB1C; NB1C vs. NB2A at 400 kA, 1.8 T



NB1B baseline (50 keV, 0.6 MW) to 4 s, then the beam under test; IRTV ΔT over 4.0–7.0 s: only the beam under test is on.

#39168 NB1C 65 keV 1 MW, $I_p = 400$ kA, $B_T = 1.8$ T
fitted D-port camera view; NuBDeC 65 keV, 1 MW, g-file 7.5 s



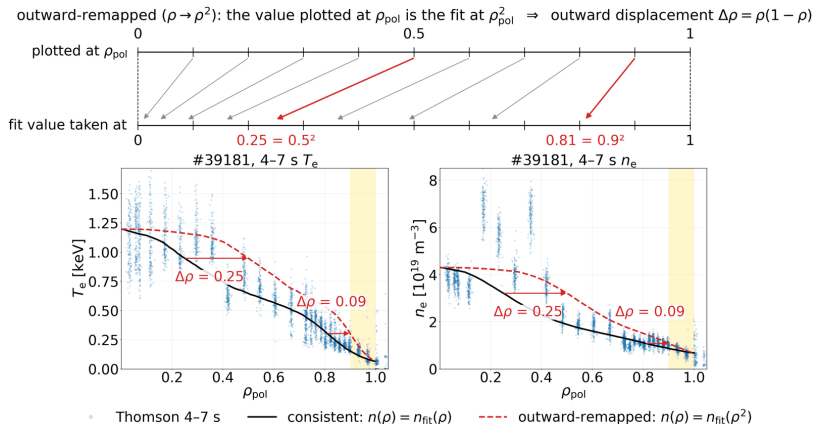
Measurement

- $\Delta T = I(7.0 \text{ s}) - I(4.0 \text{ s})$, IRTV over 4–7 s
- **Shot-to-shot difference** $\Delta_a - \Delta_b$ isolates the scanned parameter

Simulation

- NuBDeC per shot: equilibrium + n_e , T_e fit, used as the outward-mapped ($\rho \rightarrow \rho^2$) profile (next slide)
- Rendered at the **fitted D-port camera view**;
magenta: **LCFS strike line**

How the two profile inputs differ



Consistent

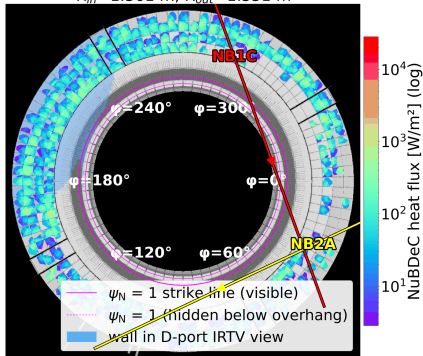
Outward-remapped
($\rho \rightarrow \rho^2$, used here)

$n_e(\rho) = n_e^{\text{fit}}(\rho)$: every fitted point at its own position (backup only)

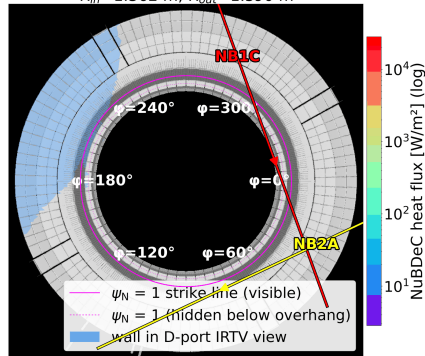
$n_e^{\text{rm}}(\rho) = n_e^{\text{fit}}(\rho^2)$: monotone remapping, axis and separatrix fixed,
outward displacement $\Delta\rho = \rho(1 - \rho)$; identical to evaluating the ρ_{pol} fit at ψ_N

LCFS strike lines along the toroidal direction

#39168 NB1C, $I_p = 400$ kA, $B_T = 1.8$ T
lower divertor, top view
 $\psi_N = 1$ strike lines (g-file 7.5 s):
 $R_{in} = 1.361$ m, $R_{out} = 1.551$ m



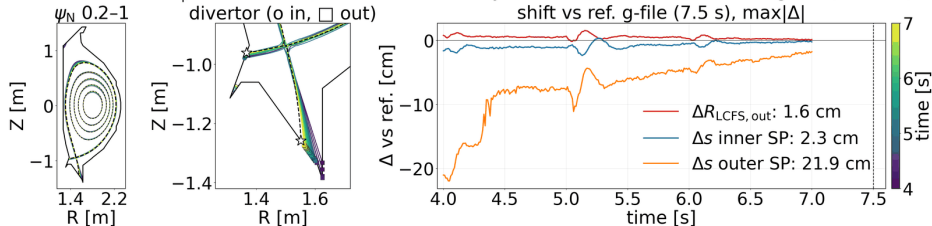
#39176 NB1C, $I_p = 600$ kA, $B_T = 1.8$ T
lower divertor, top view
 $\psi_N = 1$ strike lines (g-file 7.5 s):
 $R_{in} = 1.362$ m, $R_{out} = 1.590$ m



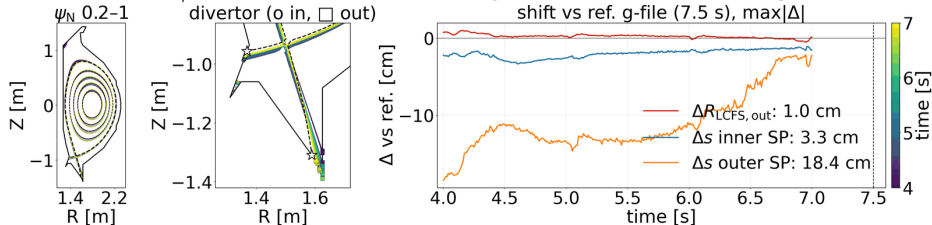
Lower divertor from above: $\psi_N = 1$ of the NuBDeC g -file on the 3D wall (dashed: hidden under the overhang). Blue: wall seen by the D-port IRTV; the strike lines ($R_{in} \approx 1.36$ m, $R_{out} \approx 1.55$ – 1.59 m) lie outside its view. Red / yellow: NuBDeC NB1C / NB2A beam axes (midplane, $R_{tan} = 1.245$ / 1.56 m; beam geometry: Sung et al., Fusion Eng. Des. 2022).

Equilibrium over 4–7 s (1/2)

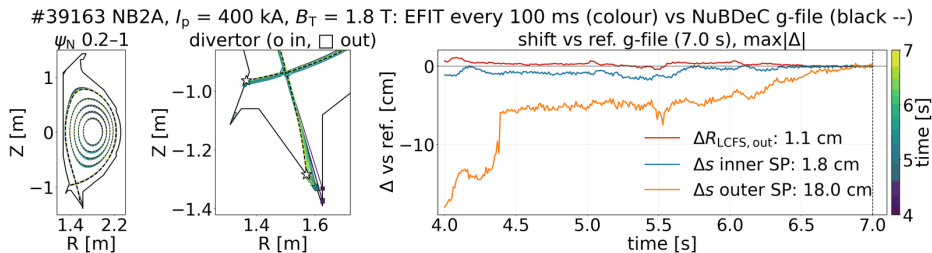
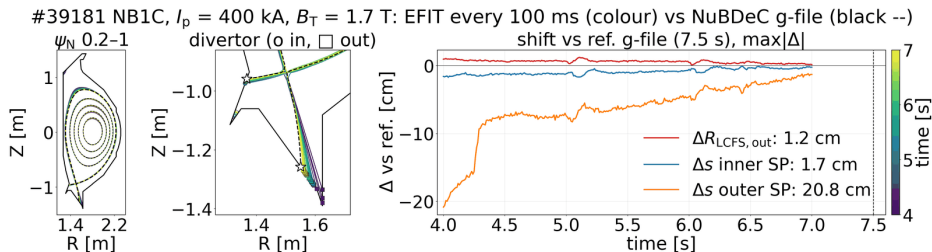
#39168 NB1C, $I_p = 400$ kA, $B_T = 1.8$ T: EFIT every 100 ms (colour) vs NuBDeC g-file (black --)



#39176 NB1C, $I_p = 600$ kA, $B_T = 1.8$ T: EFIT every 100 ms (colour) vs NuBDeC g-file (black --)



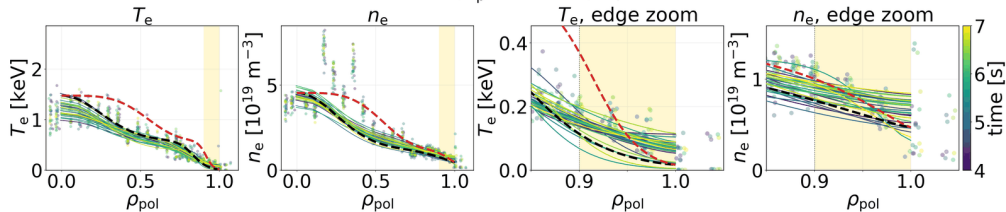
Equilibrium over 4–7 s (2/2)



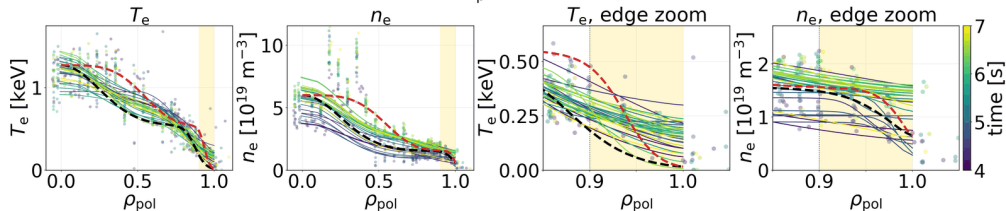
Outer-midplane LCFS within 1.0–2.8 cm; only the outer strike point moves (outside the IRTV view).

n_e , T_e profiles 4–7 s with edge zoom (1/2)

#39168 NB1C, $I_p = 400$ kA, $B_T = 1.8$ T



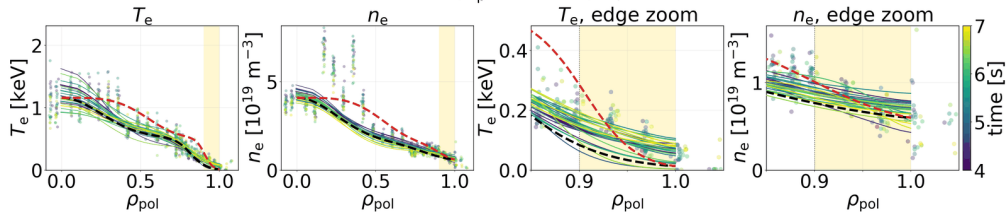
#39176 NB1C, $I_p = 600$ kA, $B_T = 1.8$ T



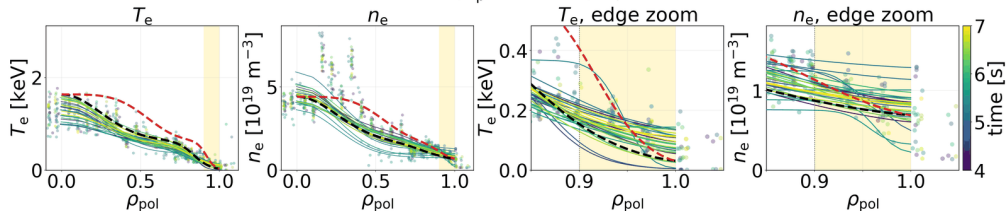
- Thomson
- mtanh fits, every 100 ms (colour = time)
- NuBDeC input
- as read by NuBDeC (col0 = ψ_N)

n_e , T_e profiles 4–7 s with edge zoom (2/2)

#39181 NB1C, $I_p = 400$ kA, $B_T = 1.7$ T



#39163 NB2A, $I_p = 400$ kA, $B_T = 1.8$ T



- Thomson
- mtanh fits, every 100 ms (colour = time)
- NuBDeC input
- as read by NuBDeC (col0 = ψ_N)

Results

I_p scan (NB1C): lower $I_p \Rightarrow$ larger ΔT , as predicted

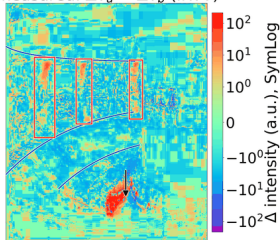
I_p scan (NB1C): 400 kA vs 600 kA
a = #39168, b = #39176

- strike point
- stabilizer boundary
- poloidal limiter

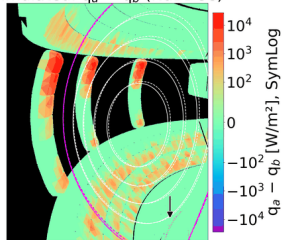
$\psi_N = 1$, #39168
 $\psi_N = 1$, #39176
 $\psi_N = 0.2-0.8$
 ○ strike pt.

thermal-ion heat flux (not prompt loss)

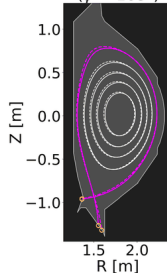
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



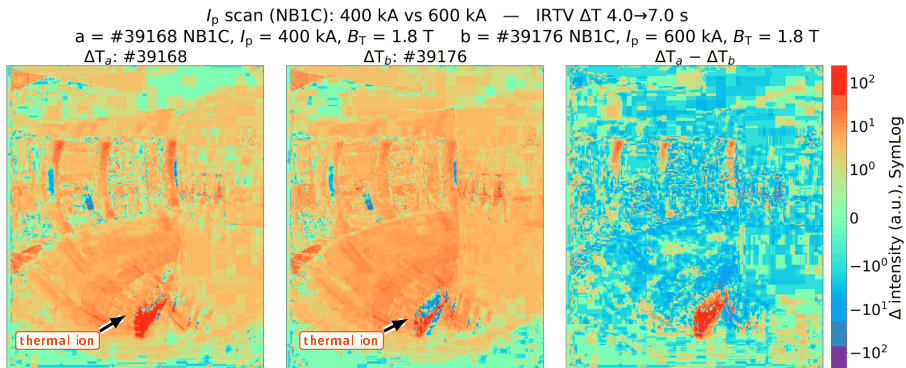
Shots

Result

Divertor spot

#39168 (400 kA) vs. #39176 (600 kA), NB1C 65 keV, 1 MW, $B_T = 1.8$ T
 ΔT at the **predicted leading-edge and limiter locations**; lower $I_p \Rightarrow$ larger ΔT
 strike point: **thermal-ion** heat flux, not prompt loss

I_p scan (NB1C): per-shot IRTV ΔT maps



IRTV ΔT (4–7 s) for #39168 (400 kA, left) and #39176 (600 kA, center), and their difference (right).

- Localized hot spots on the passive-stabilizer leading edges and lower structures are systematically stronger at 400 kA

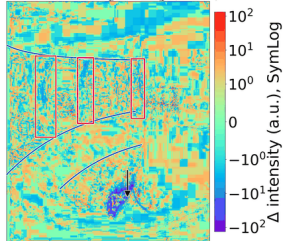
B_T scan (NB1C): a weak knob, masked by the edge birth rate

B_T scan (NB1C): 1.8 T vs 1.7 T
a = #39168, b = #39181

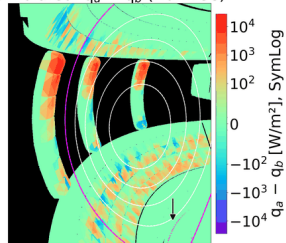
→ strike point
— stabilizer boundary
— poloidal limiter

— $\psi_N = 1$, #39168
- - $\psi_N = 1$, #39181
— $\psi_N = 0.2-0.8$
○ strike pt.

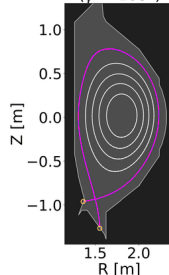
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



Measured

NuBDeC, 7.5 s inputs

Why

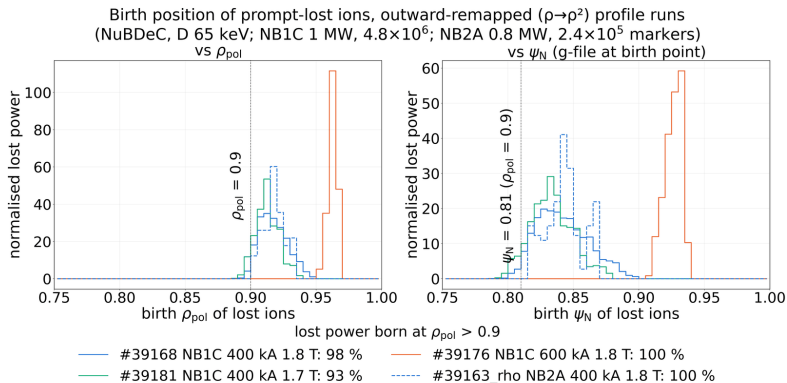
6.30 s profile

more heating at 1.7 T on limiters and passive stabilizer ($\Delta T_a - \Delta T_b < 0$)

0.53 % (1.8 T) vs. 0.17 % (1.7 T): opposite sign

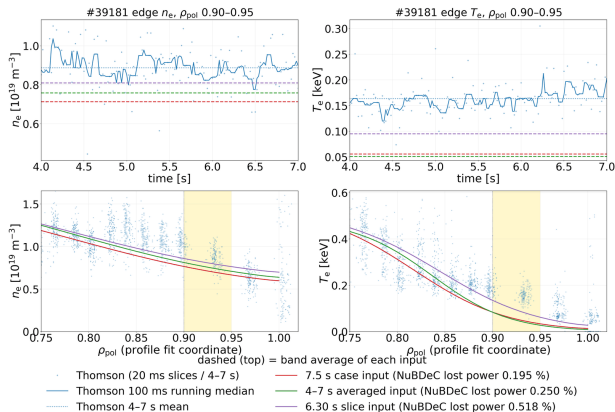
B_T -6 % is a weak knob; the edge birth rate ($\rho_{pol} > 0.9$) dominates
measured sign reproduced (supplement 3/3)

B_T scan, supplement (1/3): prompt-lost ions are born at the edge



93–100 % of the lost power is born at $\rho_{pol} > 0.9$; there T_e is too low to ionize the beam $\Rightarrow$ **edge n_e , T_e set the births**

B_T scan, supplement (2/3): #39181 edge profile inputs



	Thomson 4-7 s	7.5 s input	4-7 s avg.	6.30 s slice
edge n_e [10 ¹⁹ m ⁻³]	0.89	0.71	0.76	0.81
NuBDeC lost power	—	0.195 %	0.250 %	0.518 %

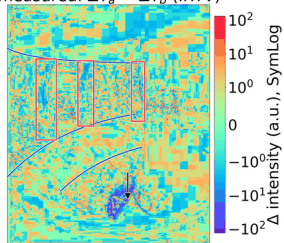
B_T scan, supplement (3/3): #39181 with the 6.30 s slice profile

B_T scan (NB1C): 1.8 T vs 1.7 T (#39181: 6.30 s slice profile, 0.48M markers)
a = #39168, b = #39181 6.3 s

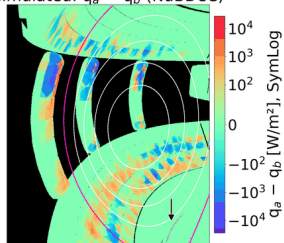
- strike point
- stabilizer boundary
- poloidal limiter

- $\psi_N = 1$, #39168
- $\psi_N = 1$, #39181 6.3 s
- $\psi_N = 0.2-0.8$
- strike pt.

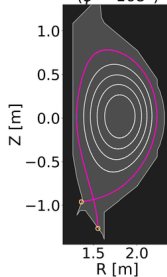
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



NuBDeC, #39181 (remapped, 4.8×10^5)	lost power	lost / born at $\rho_{pol} > 0.9$	IRTV view	limiters
7.5 s input	$0.195 \pm 0.006 \%$	60 %	0.44	0.36
4-7 s averaged	$0.250 \pm 0.007 \%$	55 %	0.53	0.55
6.30 s slice	$0.518 \pm 0.010 \%$	65 %	1.07	1.18
#39168, 7.5 s (4.8×10^6)	$0.531 \pm 0.003 \%$	62 %	1	1

IRTV view / limiters: wall power rel. to #39168; 6.30 s = highest edge; next: slice-resolved 4-7 s runs. $\pm$: Poisson (single runs).

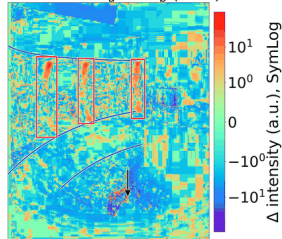
Beam-source scan: NB1C vs. NB2A at $I_p = 400$ kA, $B_T = 1.8$ T

beam scan: NB1C (1 MW) vs NB2A (0.8 MW), $I_p = 400$ kA, $B_T = 1.8$ T
a = #39168, b = #39163

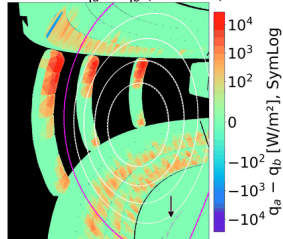
→ strike point
— stabilizer boundary
— poloidal limiter

— $\psi_N = 1$, #39168
- - $\psi_N = 1$, #39163
— $\psi_N = 0.2-0.8$
○ strike pt.

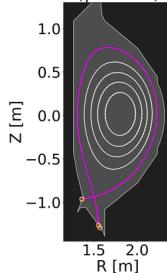
measured: $\Delta T_a - \Delta T_b$ (IRTV)



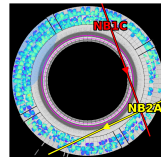
simulated: $q_a - q_b$ (NuBDeC)



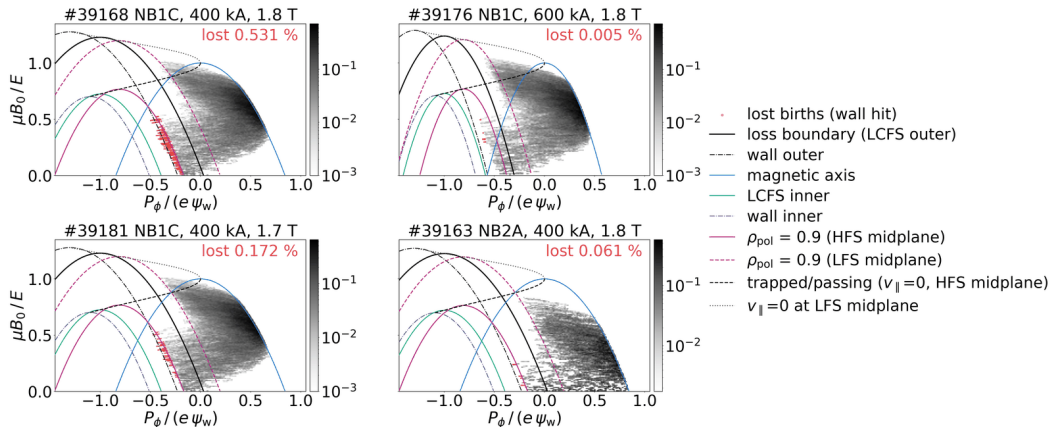
poloidal view
($\phi = 168^\circ$)



Shots #39168 NB1C (1 MW) vs. #39163 NB2A (0.8 MW); no power normalization
Geometry NB1C tangency radius 1.245 m, smaller than NB2A 1.56 m (NB1A 1.486 m)
 $\Rightarrow$ smaller $v_{||}/v$ at birth $\Rightarrow$ larger drift D
Result measured and simulated: **more limiter heating with NB1C**
NuBDeC NB2A/NB1C wall power 0.10 (IRTV view 0.10, limiter boxes 0.11)
Note #39163: remapped profile, only 2.4×10^5 markers — noisy, boundaries resolved

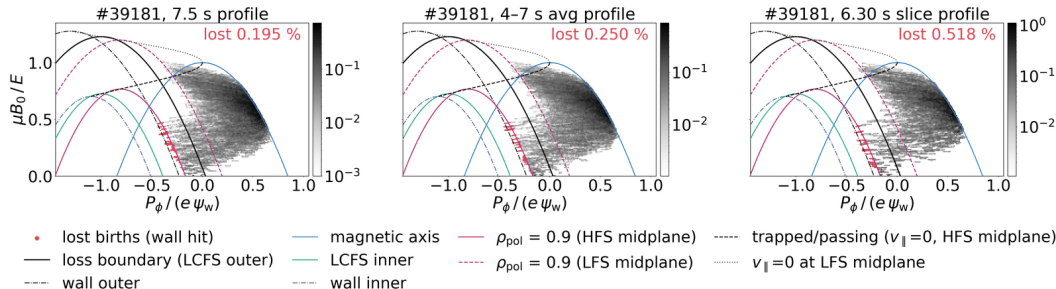


Where prompt-lost ions come from: birth phase space



Lost ions red: born at the HFS edge, between LCFS-outer and wall-outer loss boundaries, at $\rho_{pol} = 0.9$
 Runs NuBDeC, D 65 keV; NB1C 1 MW, 4.8×10^6 ; NB2A #39163 0.8 MW, 2.4×10^5 markers

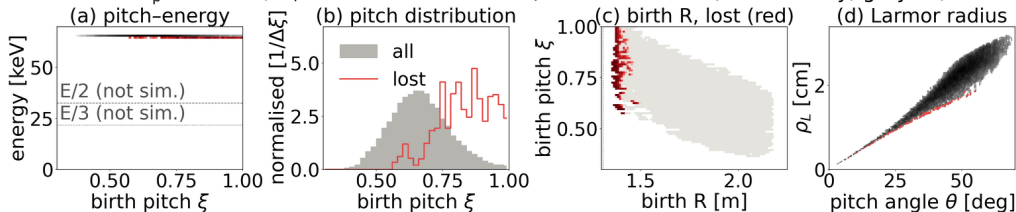
Birth phase space, #39181: 7.5 s, 4–7 s average and 6.30 s profiles



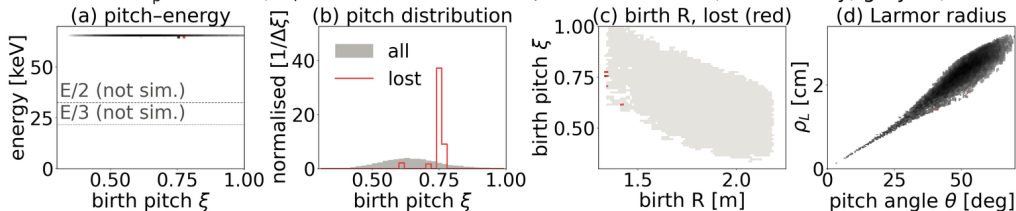
All three: outward-remapped ($\rho \rightarrow \rho^2$) profile, 4.8×10^5 markers; they differ only in the fitted time: 7.5 s, 4–7 s average, 6.30 s (highest edge). Lost births fill the same band; the edge input sets how many.

Pitch-energy, pitch, birth R and Larmor radius (1/2)

#39168 NB1C $I_p = 400$ kA, $B_T = 1.8$ T: lost 0.531 % (4.8×10^6 markers, 65 keV only; grey all, red lost)

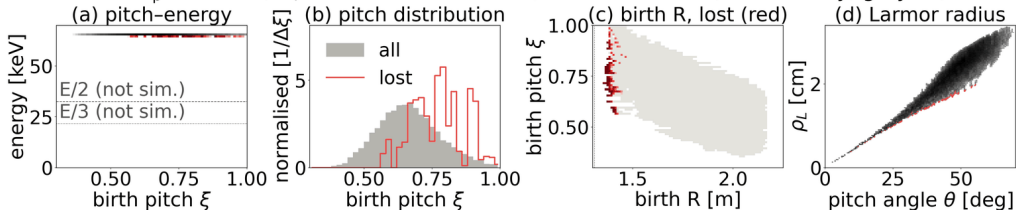


#39176 NB1C $I_p = 600$ kA, $B_T = 1.8$ T: lost 0.005 % (4.8×10^6 markers, 65 keV only; grey all, red lost)

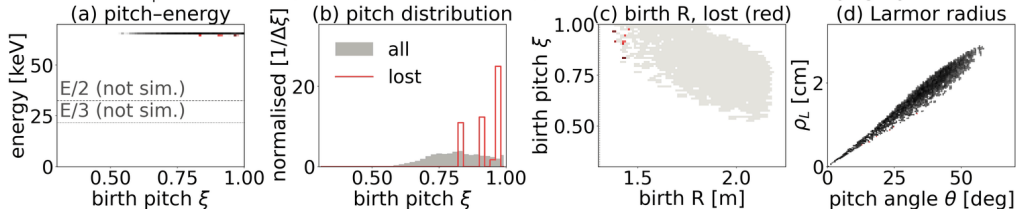


Pitch-energy, pitch, birth R and Larmor radius (2/2)

#39181 NB1C $I_p = 400$ kA, $B_T = 1.7$ T: lost 0.172 % (4.8×10^6 markers, 65 keV only; grey all, red lost)



#39163 NB2A $I_p = 400$ kA, $B_T = 1.8$ T: lost 0.061 % (2.4×10^5 markers, 65 keV only; grey all, red lost)



Lost ions: $\rho_L \lesssim 2$ cm, born at the HFS edge ($R \approx 1.34$ – 1.49 m), smaller than the HFS LCFS-wall gap (3.6–4.4 cm) $\Rightarrow$ drift-orbit loss.

Assumptions & limitations of the comparison

- **Thermal-ion losses** are confined to the divertor region $\Rightarrow$ fall outside the predicted prompt-loss footprints in the IRTV field of view
- **Delayed orbit losses** deviate only slightly from the prompt-loss distribution
- Comparison is **qualitative**: footprint *location* and *parametric trend*, not absolute heat-flux magnitude
 - IRTV Δ intensity in a.u. (linear) vs. simulated heat flux in W/m^2 (log scale)
 - Surface emissivity, deposit layers, and camera calibration limit quantitative use
- 2 / 23 discharges excluded (H-mode / back-transition)
- **Profile input**: outward-remapped ($\rho \rightarrow \rho^2$) sensitivity profile, identical to evaluating the ρ_{pol} fit at ψ_N (next to methodology)
- **Edge profile input**: prompt-lost ions are born at $\rho_{\text{pol}} > 0.9$, where T_e is too low to ionize the beam neutrals efficiently, so the loss depends on the edge T_e profile

Conclusions & Outlook

First qualitative benchmark of CAD-based prompt-loss prediction on KSTAR

- NuBDeC CAD-based high-fidelity prompt-loss predictions are **validated against IRTV PFC temperature rise**
- Localized ΔT appears at the **predicted leading-edge and poloidal-limiter locations**
- Measured I_p trend (NB1C) and source trend (NB1C > NB2A at 400 kA) follow NuBDeC, with **toroidal drift** as the main driver
- B_T scan: 1.8 $\rightarrow$ 1.7 T is a weak knob; the simulated loss follows the beam births at the edge ($\rho_{pol} > 0.9$), i.e. the edge T_e/n_e input. With the highest-edge (6.30 s) #39181 profile the **measured sign on the limiters is reproduced**; a slice-resolved 4–7 s simulation is the next step

Establishes a standardized, error-resistant foundation for **synthetic diagnostics** of fast-ion wall loads.

Outlook: toward an AI-native treatment of engineering detail

- **Quantitative predictive model** for the KSTAR case as next step
- **Surrogate model** trained on the experimentally validated dataset:
 - predicts prompt-loss heat flux *directly on the unstructured PFC mesh*
 - conditioned on magnetic equilibrium, beam source, and as-built geometry
 - preserves full axial asymmetry while collapsing per-case cost
- Enables:
 - exhaustive NBI parameter scans during **conceptual design** of future devices (ITER, CPD, DEMO)
 - **between-shot heat-load guidance** — avoid wasted discharges, fine-tune heating to each experiment's mission
- Integration into the KFE **digital twin platform**

References & Acknowledgement

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3. W. Tang et al., arXiv:2409.03112 (2024).
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9. E. Hirvijoki et al., Comput. Phys. Commun. **185** (2014) 1310–1321. (ASCOT)
10. K. Miyamoto, *Plasma Physics for Controlled Fusion* (Springer, 2016), Chap. II, p. 30. (drift orbits)
11. C. Sung et al., Fusion Eng. Des. **185** (2022) 113320. (KSTAR NBI deposition, beam geometry)

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Thank you!

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Backup: session summary & scan matrix

4-hour session: 21 / 23 discharges successfully configured in LSN L-mode flat-top.

Shot #	I_p [kA]	B_T [T]	Following beam	Role in scan
39168	400	1.8	NB1C @ 65 keV, 1.0 MW	reference (max drift)
39176	600	1.8	NB1C @ 65 keV, 1.0 MW	I_p scan
39181	400	1.7	NB1C @ 65 keV, 1.0 MW	B_T scan
39163	400	1.8	NB2A @ 55 keV, 0.8 MW	beam-source pair (400 kA, 1.8 T)

Baseline beam in all shots: NB1B @ 50 keV, 0.6 MW. Full matrix also includes NB2B/NB2C sources and $I_p = 500$ kA; representative pairs shown here. IR calibration for the low-temperature range performed on passive-stabilizer shield tiles. NuBDeC equilibrium at 7.5 s (NB1C) / 7.0 s (NB2A).

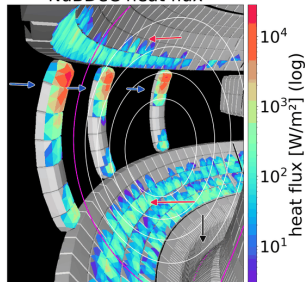
Backup: per-shot IRTV vs. simulation renders (1/4)

#39168 NB1C 65 keV 1 MW, $I_p = 400$ kA, $B_T = 1.8$ T
fitted D-port camera view; NuBDeC 65 keV, 1 MW, g-file 7.5 s

IRTV frame @ 7.0 s



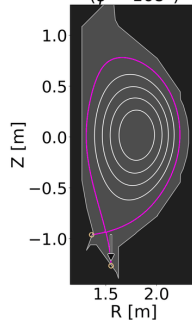
NuBDeC heat flux



— $\psi_N = 1$
— $\psi_N = 0.2-0.8$

→ strike point → poloidal limiter → passive stabilizer

poloidal view
($\phi = 168^\circ$)



○ strike pt.

Shared colour scale; heat flux rendered at the fitted D-port camera position. Magenta: LCFS strike line on the wall; white: $\psi_N = 0.2-0.8$ in the poloidal plane $\phi = 168^\circ$.

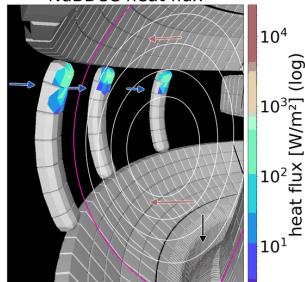
Backup: per-shot IRTV vs. simulation renders (2/4)

#39176 NB1C 65 keV 1 MW, $I_p = 600$ kA, $B_T = 1.8$ T
fitted D-port camera view; NuBDeC 65 keV, 1 MW, g-file 7.5 s

IRTV frame @ 7.0 s



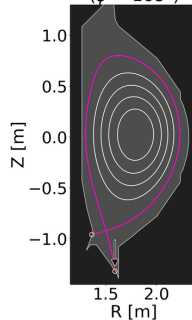
NuBDeC heat flux



— $\psi_N = 1$
— $\psi_N = 0.2-0.8$

→ strike point → poloidal limiter → passive stabilizer

poloidal view
($\phi = 168^\circ$)



○ strike pt.

Shared colour scale; heat flux rendered at the fitted D-port camera position. Magenta: LCFS strike line on the wall; white: $\psi_N = 0.2-0.8$ in the poloidal plane $\phi = 168^\circ$.

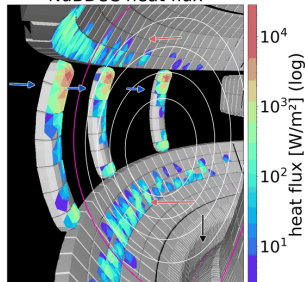
Backup: per-shot IRTV vs. simulation renders (3/4)

#39181 NB1C 65 keV 1 MW, $I_p = 400$ kA, $B_T = 1.7$ T
fitted D-port camera view; NuBDeC 65 keV, 1 MW, g-file 7.5 s

IRTV frame @ 7.0 s



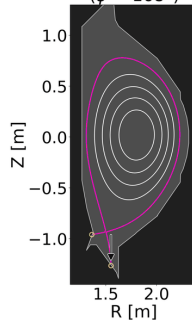
NuBDeC heat flux



— $\psi_N = 1$
— $\psi_N = 0.2-0.8$

→ strike point → poloidal limiter → passive stabilizer

poloidal view
($\phi = 168^\circ$)

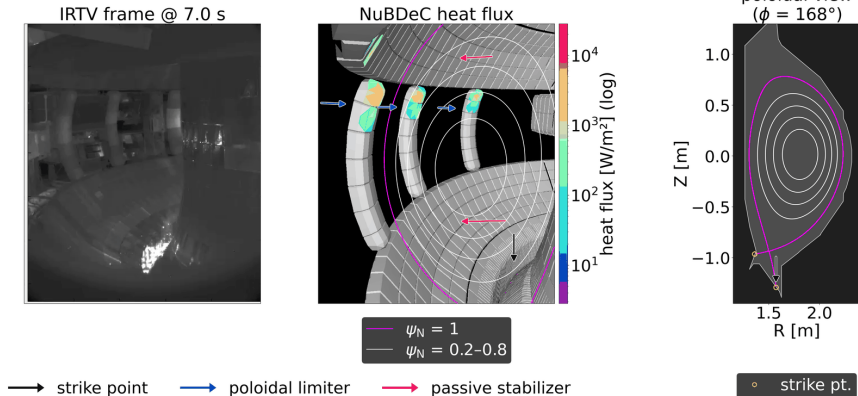


○ strike pt.

Shared colour scale; heat flux rendered at the fitted D-port camera position. Magenta: LCFS strike line on the wall; white: $\psi_N = 0.2-0.8$ in the poloidal plane $\phi = 168^\circ$.

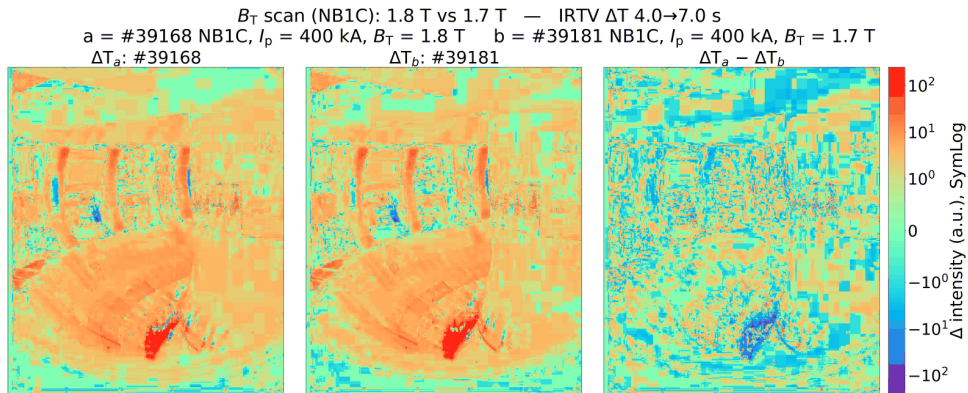
Backup: per-shot IRTV vs. simulation renders (4/4)

#39163 NB2A 55 keV 0.8 MW, $I_p = 400$ kA, $B_T = 1.8$ T
fitted D-port camera view; NuBDeC 65 keV, 0.8 MW, g-file 7 s



#39163 (NB2A, 0.8 MW, 2.4×10^5 markers). Shared colour scale; heat flux rendered at the fitted D-port camera position. Magenta: LCFS strike line on the wall; white: $\psi_N = 0.2-0.8$ in the poloidal plane $\phi = 168^\circ$.

Backup: B_T scan per-shot IRTV ΔT



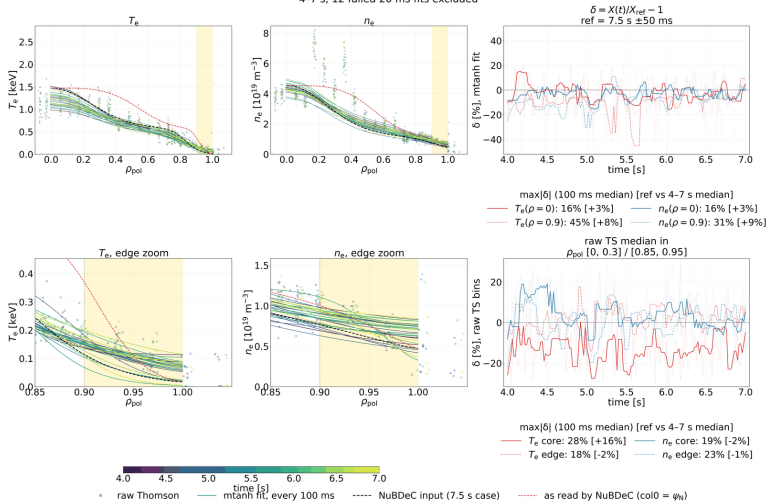
IRTV ΔT (4–7 s): #39168 ($B_T = 1.8$ T) vs. #39181 ($B_T = 1.7$ T), and their difference.

Backup: why one simulation time (7.0 / 7.5 s) for the 4–7 s ΔT ?

1. $\Delta T = I(7.0\text{ s}) - I(4.0\text{ s})$ is an **accumulated** response: one NuBDeC snapshot is compared with the 3 s-integrated wall heating
 - the prompt-loss footprint is set by the equilibrium and the beam geometry; density fluctuations of this size change the beam deposition only weakly
2. Reference times: **NB1C at 7.5 s** (#39168, #39176, #39181), **NB2A at 7.0 s** (#39163)
3. Over 4–7 s the plasma is close to the reference:
 - equilibrium (EFIT, 10 ms): outer-midplane LCFS within 1.0–2.8 cm (mean 0.2–0.6 cm), inner strike point within 1.7–3.7 cm; only the outer strike point moves (15–22 cm along the target, mostly 4.0–4.5 s)
 - profiles (Thomson + mtanh fit): core T_e , n_e at the reference time within $\pm 15\%$ of the 4–7 s median for #39163, #39168, #39181; exception #39176 (n_e –28 %, rising)

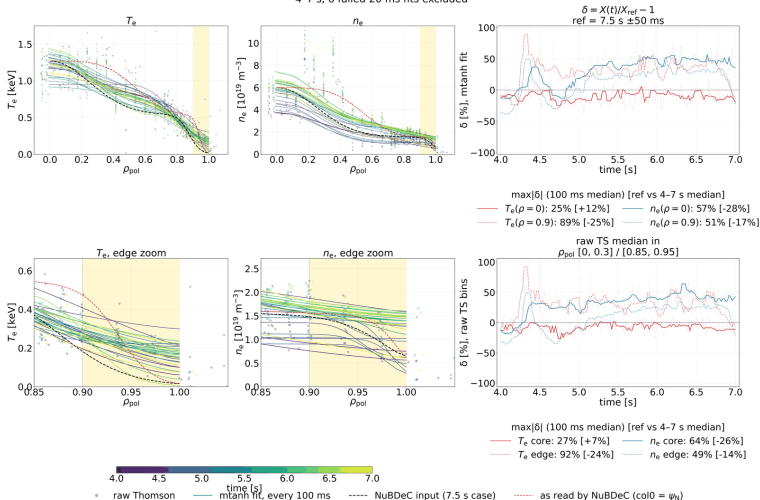
Backup: n_e , T_e profiles 4–7 s, #39168 (NB1C, $I_p = 400$ kA, $B_T = 1.8$ T)

Profile sweep #39168 NB1C, $I_p = 400$ kA, $B_T = 1.8$ T
4–7 s, 12 failed 20 ms fits excluded



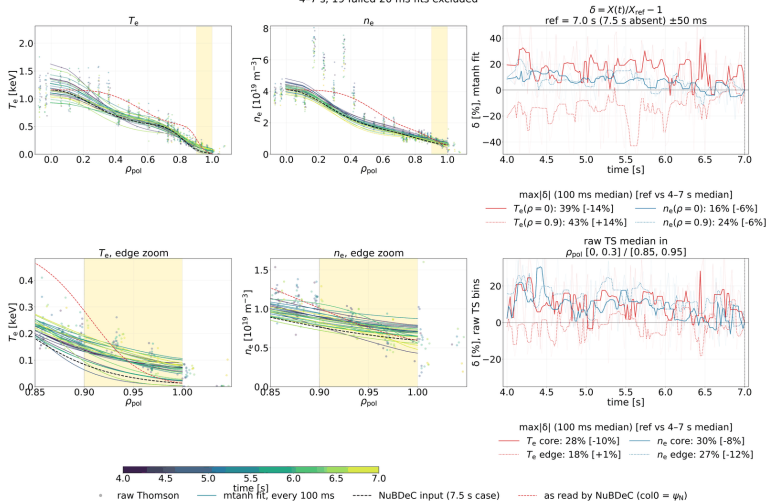
Backup: n_e , T_e profiles 4–7 s, #39176 (NB1C, $I_p = 600$ kA, $B_T = 1.8$ T)

Profile sweep #39176 NB1C, $I_p = 600$ kA, $B_T = 1.8$ T
4–7 s, 6 failed 20 ms fits excluded



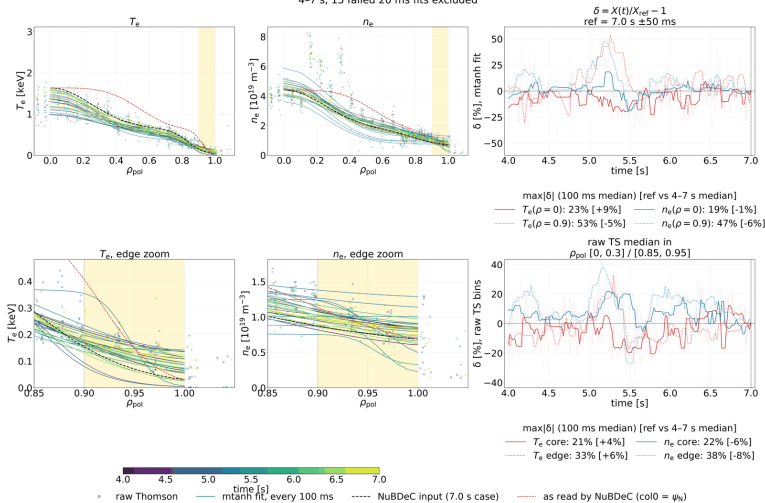
Backup: n_e , T_e profiles 4–7 s, #39181 (NB1C, $I_p = 400$ kA, $B_T = 1.7$ T)

Profile sweep #39181 NB1C, $I_p = 400$ kA, $B_T = 1.7$ T
4–7 s, 19 failed 20 ms fits excluded

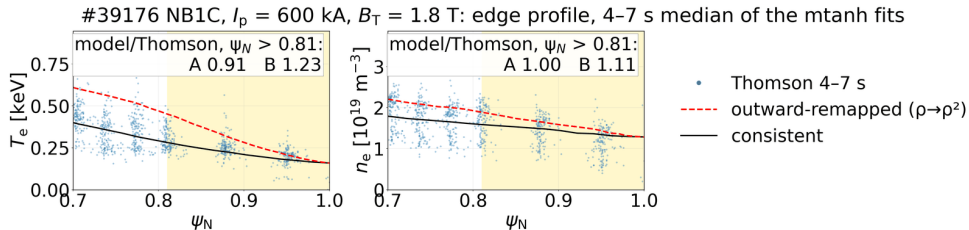
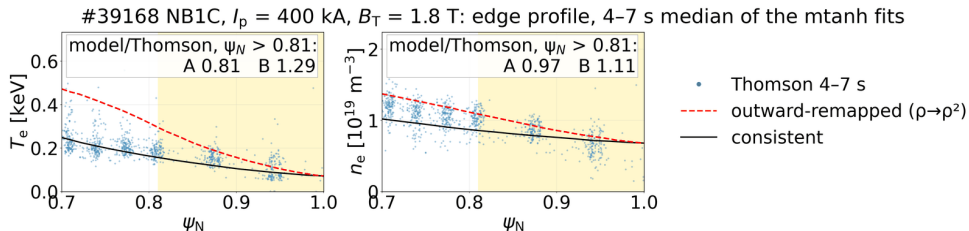


Backup: n_e , T_e profiles 4–7 s, #39163 (NB2A, $I_p = 400$ kA, $B_T = 1.8$ T)

Profile sweep #39163 NB2A, $I_p = 400$ kA, $B_T = 1.8$ T
4–7 s, 15 failed 20 ms fits excluded

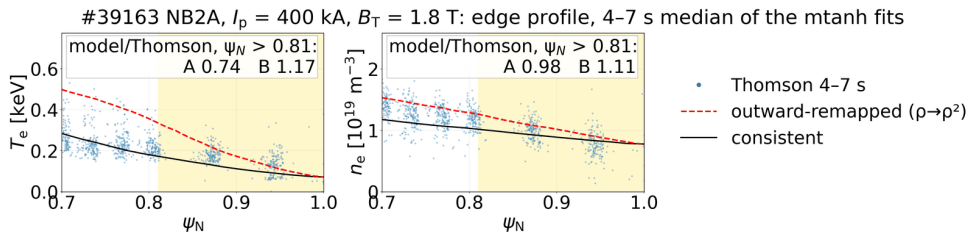
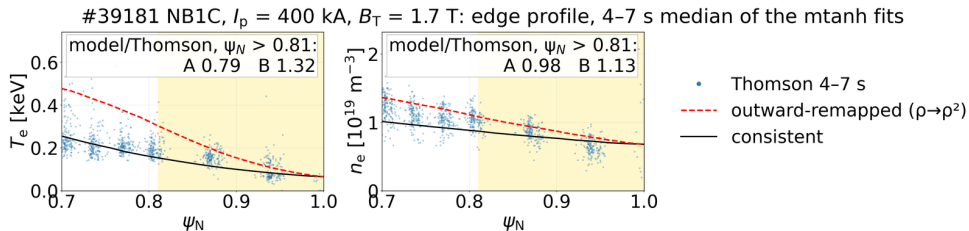


Backup: edge profiles, remapped vs consistent vs Thomson (1/2)



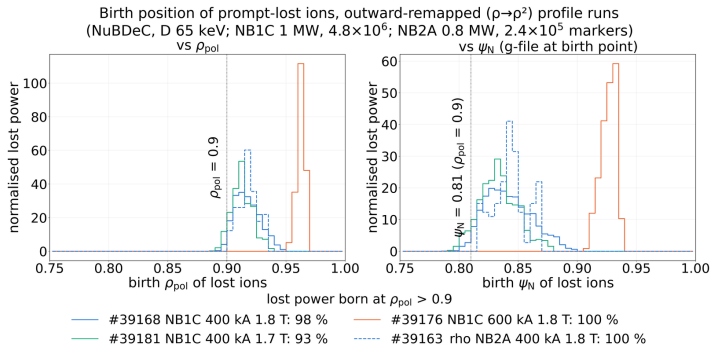
4–7 s median of the Thomson-only mtanh fits $f(\rho_{pol})$. Outward-remapped ($\rho \rightarrow \rho^2$): $f(\rho_{pol}^2)$ at ρ_{pol} ; consistent: $f(\rho_{pol})$.

Backup: edge profiles, remapped vs consistent vs Thomson (2/2)



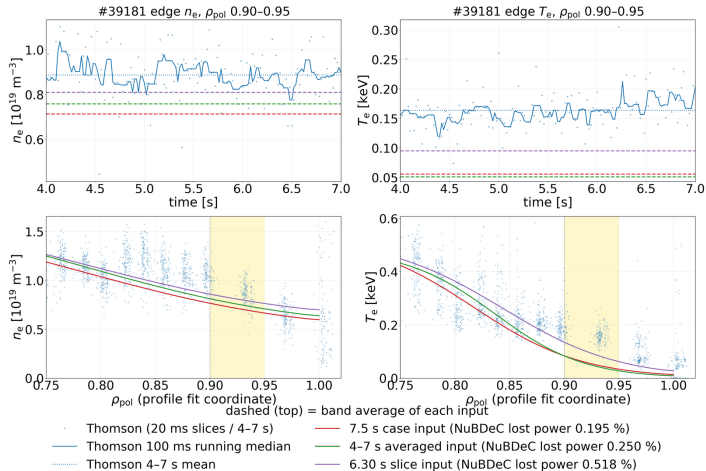
For $\psi_N > 0.81$: T_e +17 to +32 % (remapped), –9 to –26 % (consistent); n_e +11 to +13 % (remapped), within 3 % (consistent).

Backup: prompt-lost ions are born at the edge, $\rho_{\text{pol}} > 0.9$



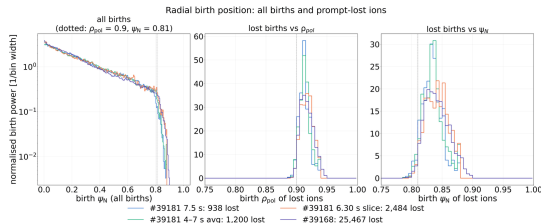
- Outward-remapped ($\rho \rightarrow \rho^2$) profile runs; left and right show the same lost ions, birth position as ρ_{pol} and as $\psi_N = \rho_{\text{pol}}^2$ (g-file)
- 93–100 % of the lost power is born at $\rho_{\text{pol}} > 0.9$ (ψ_N 0.79–0.94); no marker is born beyond $\psi_N = 0.95$
- The edge profile ($\rho_{\text{pol}} \gtrsim 0.9$) therefore sets the prompt-loss source

Backup: #39181 edge n_e , T_e over 4–7 s vs. the NuBDeC inputs



Top: Thomson ρ_{pol} 0.90–0.95 per slice; bottom: profiles. 7.5 s input edge n_e –20 % vs. the 4–7 s mean.

Backup: #39181 re-simulated with the 4–7 s averaged profile

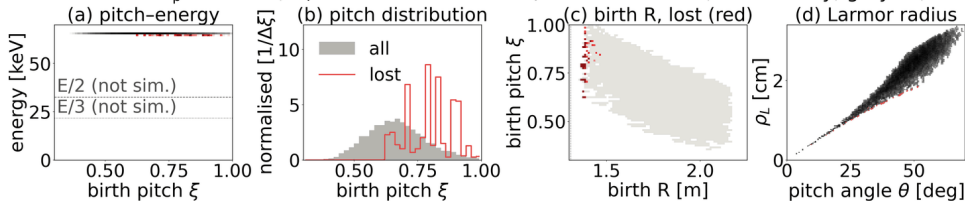


NuBDeC run (#39181, 7.5 s g-file)	markers	lost	lost power	$\rho_{pol} > 0.9$ births (lost out of these)
7.5 s profile	4.8×10^5	938	$0.195 \pm 0.006 \%$	0.31 % (60 %)
4–7 s averaged profile (Thomson)	4.8×10^5	1200	$0.250 \pm 0.007 \%$	0.44 % (55 %)
reference: 7.5 s profile	4.8×10^6	8254	$0.172 \pm 0.002 \%$	0.27 % (60 %)
reference: #39168 (1.8 T), 7.5 s profile	4.8×10^6	25467	$0.531 \pm 0.003 \%$	0.84 % (62 %)

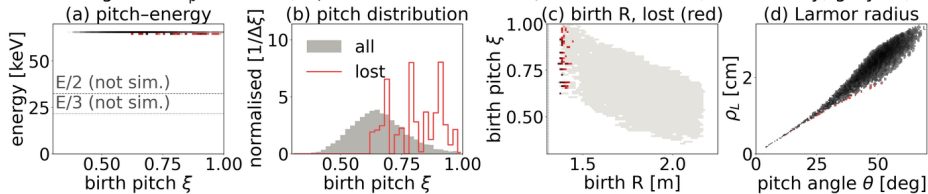
- 4–7 s averaged profile: +28 % loss, from +41 % births at $\rho_{pol} > 0.9$ (T_e stays high enough to ionize the beam slightly further out); 55–62 % of those births are lost in every run, at 1.7 and 1.8 T $\Rightarrow$ the loss follows the edge birth count
- No birth beyond $\psi_N = 0.88$ in either run (depo_Psi_out = 0.90 is not used by the fast-ion-loss executable)
- $\pm$: marker-counting (Poisson) estimate, lost power/ $\sqrt{N_{lost}}$; single runs, no ensemble

Backup: pitch-energy and Larmor radius, #39181 with the 7.5 s and 4–7 s profiles

#39181 7.5 s NB1C $I_p = 400$ kA, $B_T = 1.7$ T: lost 0.195 % (4.8×10^5 markers, 65 keV only; grey all, red lost)



#39181 4–7 s avg NB1C $I_p = 400$ kA, $B_T = 1.7$ T: lost 0.250 % (4.8×10^5 markers, 65 keV only; grey all, red lost)



Backup: B_T scan, #39181 with the 4–7 s averaged profile

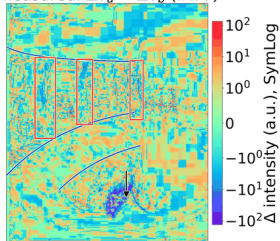
B_T scan (NB1C): 1.8 T vs 1.7 T (#39181: 4–7 s avg profile, 0.48M markers)

a = #39168, b = #39181 4–7 s avg

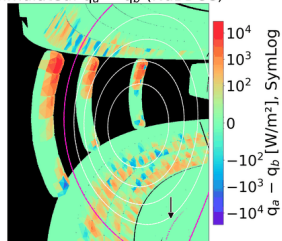
- strike point
- stabilizer boundary
- poloidal limiter

$\psi_N = 1$, #39168
 $\psi_N = 1$, #39181 4–7 s avg
 $\psi_N = 0.2-0.8$
 ○ strike pt.

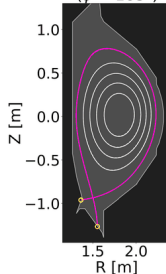
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



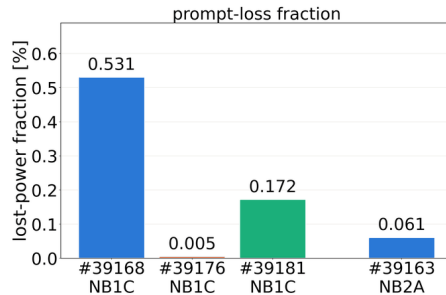
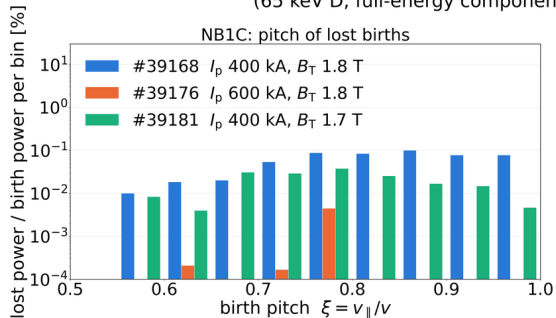
NuBDeC (remapped profiles)	lost power	births at $\rho_{pol} > 0.9$	lost out of these births
#39181, 7.5 s input (4.8×10^5 markers)	$0.195 \pm 0.006 \%$	0.31 %	60 %
#39181, 4–7 s averaged input (4.8×10^5)	$0.250 \pm 0.007 \%$	0.44 %	55 %
#39168, 7.5 s input (4.8×10^6)	$0.531 \pm 0.003 \%$	0.84 %	62 %

4–7 s profile: +28 % loss (more edge births), still below #39168 $\Rightarrow q_a - q_b > 0$ on the limiters.

$\pm$: Poisson (single runs, no ensemble).

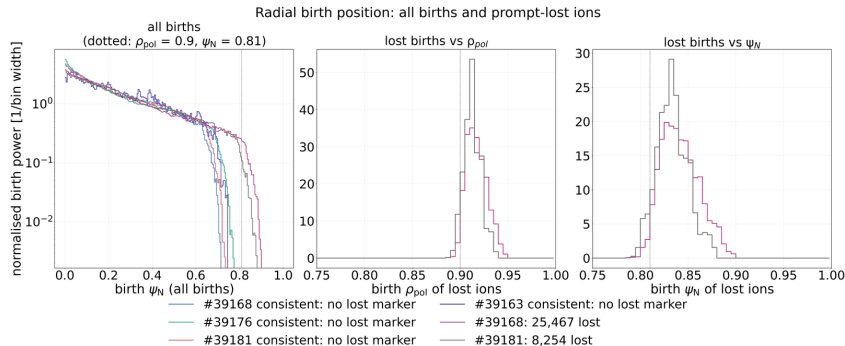
Backup: pitch of lost ions and prompt-loss fraction

Prompt losses vs I_p , B_T and beam source
(65 keV D, full-energy component only; E/2, E/3 not included)



Full-energy component only ($E = 65$ keV, IRATIO 1:0:0); the $E/2$, $E/3$ components are not included (not effective in this study).

Backup: consistent profiles — no prompt loss



Runs #39168, #39176, #39181 (NB1C, 1 MW), #39163 (NB2A, 0.8 MW)

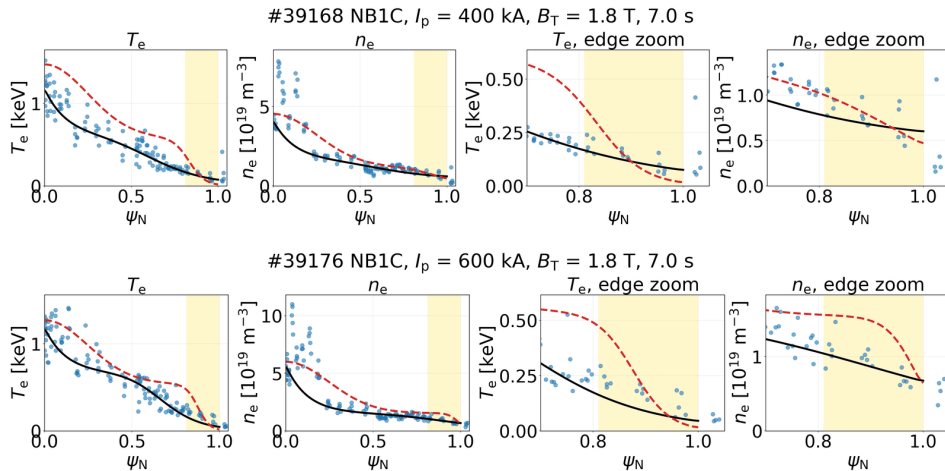
Profile consistent: 7.0 s Thomson mtanh fit used at its own ρ_{pol}

Result 0 lost markers, 0 W on the wall in all four runs

Why births end at ψ_N 0.71–0.78 (T_e too low further out) $\Rightarrow$ none at $\rho_{pol} > 0.9$

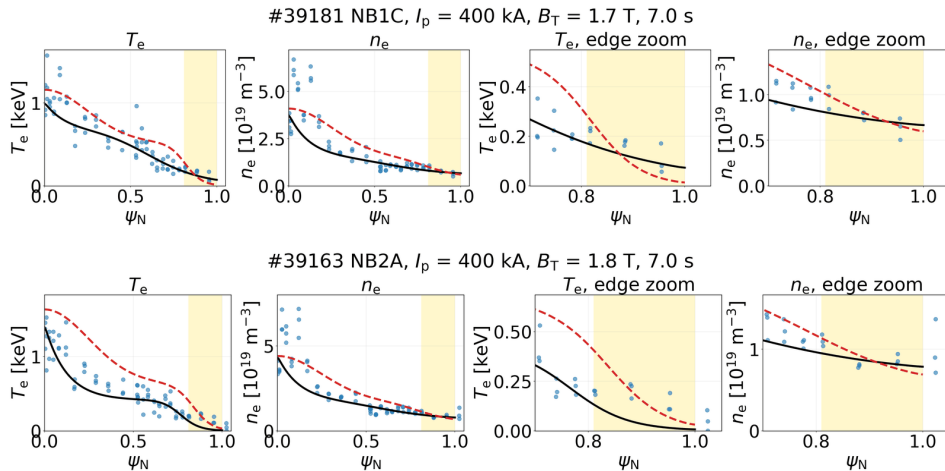
So B_T / I_p / source renders are empty; the remapped profile keeps the edge births

Backup: consistent-profile inputs vs Thomson, 7.0 s (1/2)



- Thomson 6.96–7.04 s — consistent - - - outward-remapped ($\rho \rightarrow \rho^2$)

Backup: consistent-profile inputs vs Thomson, 7.0 s (2/2)



- Thomson 6.96–7.04 s — consistent - - - outward-remapped ($\rho \rightarrow \rho^2$)

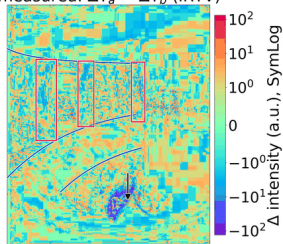
Backup: consistent-profile runs, B_T scan (#39168 vs #39181)

B_T scan, consistent profiles: 1.8 T vs 1.7 T
a = #39168 ψ_N , b = #39181 ψ_N

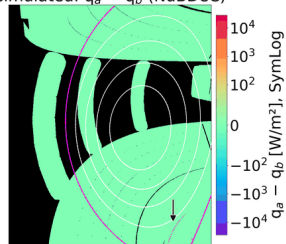
→ strike point
— stabilizer boundary
— poloidal limiter

— $\psi_N = 1$, #39168 ψ_N
- - $\psi_N = 1$, #39181 ψ_N
— $\psi_N = 0.2-0.8$
○ strike pt.

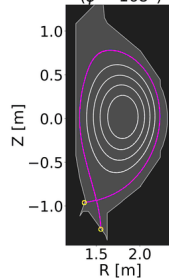
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



Simulated side empty: no lost marker in either run.

Backup: consistent-profile runs, I_p scan (#39168 vs #39176)

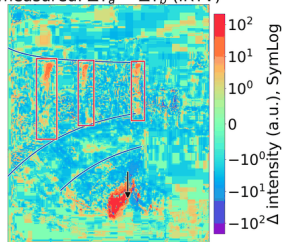
I_p scan, consistent profiles: 400 vs 600 kA

a = #39168 ψ_N , b = #39176 ψ_N

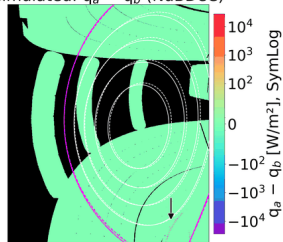
- strike point
- stabilizer boundary
- poloidal limiter

- $\psi_N = 1$, #39168 ψ_N
- - - $\psi_N = 1$, #39176 ψ_N
- $\psi_N = 0.2-0.8$
- strike pt.

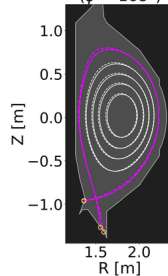
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)



poloidal view
($\phi = 168^\circ$)



Simulated side empty: no lost marker in either run.

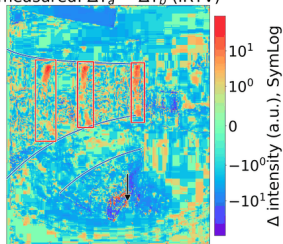
Backup: consistent-profile runs, beam-source scan (#39168 vs #39163)

beam scan, consistent profiles: NB1C (1 MW) vs NB2A (0.8 MW)
a = #39168 ψ_N , b = #39163 ψ_N

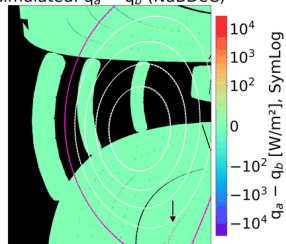
- strike point
- stabilizer boundary
- poloidal limiter

- $\psi_N = 1$, #39168 ψ_N
- - - $\psi_N = 1$, #39163 ψ_N
- $\psi_N = 0.2-0.8$
- strike pt.

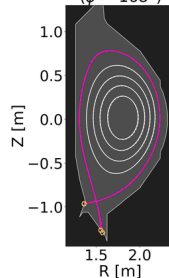
measured: $\Delta T_a - \Delta T_b$ (IRTV)



simulated: $q_a - q_b$ (NuBDeC)

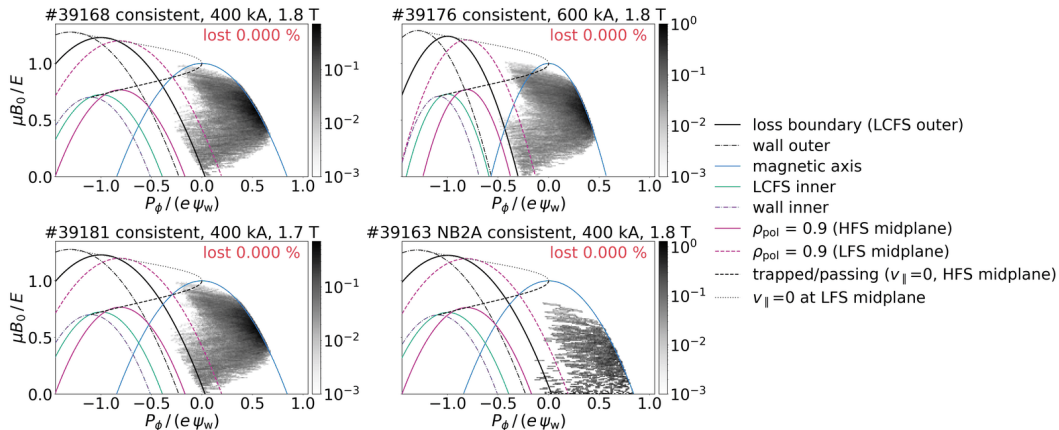


poloidal view
($\phi = 168^\circ$)



Simulated side empty: no lost marker in either run.

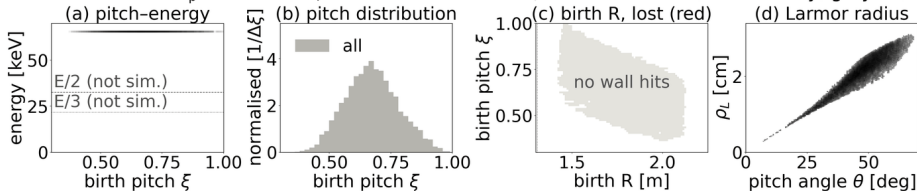
Backup: consistent-profile runs, birth phase space



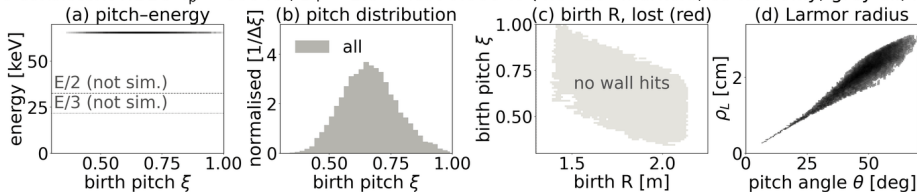
No lost births in any of the four runs (incl. NB2A #39163): births end inside $\rho_{pol} = 0.9$ (magenta).

Backup: consistent-profile runs, pitch–energy, pitch, birth R , Larmor radius (1/2)

#39168 consistent NB1C $I_p = 400$ kA, $B_T = 1.8$ T: lost 0.000 % (4.8×10^6 markers, 65 keV only; grey all, red lost)

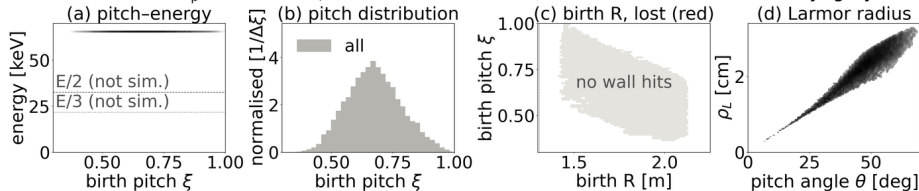


#39176 consistent NB1C $I_p = 600$ kA, $B_T = 1.8$ T: lost 0.000 % (4.8×10^6 markers, 65 keV only; grey all, red lost)



Backup: consistent-profile runs, pitch–energy, pitch, birth R , Larmor radius (2/2)

#39181 consistent NB1C $I_p = 400$ kA, $B_T = 1.7$ T: lost 0.000 % (4.8×10^6 markers, 65 keV only; grey all, red lost)



#39163 consistent NB2A $I_p = 400$ kA, $B_T = 1.8$ T: lost 0.000 % (4.8×10^5 markers, 65 keV only; grey all, red lost)

